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Empirical Measurements of Small Unmanned Aerial Vehicle Co-Axial Rotor Systems

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ABSTRACT

Small unmanned aerial vehicles (SUAV) are beginning to dominate the area of intelligence, surveillance, target acquisition and reconnaissance (ISTAR) in forward operating battlefield scenarios. Of particular interest are vertical take-off and landing (VTOL) variants. Within this category co-axial rotor designs have been adopted due to their inherent advantages of size and power to weight ratio. The inter-rotor spacing attribute of a co-axial rotor system appears to offer insight into the optimum design characteristic. The H/D ratio has been cited as a significant factor in many research papers, but to date has lacked an empirical value or an optimal dimensionless condition. In this paper the H/D ratio of a SUAV has been explored thoroughly, reviewing the performance of these systems at incremental stages, the findings from this study have shown that a range of H/D ratios in the region of (0.41-0.65) is advantageous in the performance of SUAV systems. This finding lends itself to the theory of inter-rotor spacing as a non-dimensionally similar figure, which cannot be applied across a spectrum of systems; this could be attributed to the viscous losses of flight at low Reynolds Numbers (< 50,000).

Keywords: Unmanned Aerial Vehicle, Co-Axial, Rotor, H/D Ratio, Empirical Measurements.

1. Introduction

The area of unmanned aerial vehicles (UAV) is a technology which is growing exponentially in terms of technological advancement and international adoption. The uses of UAVs are associated with many diverse applications. These applications range from Search and Rescue [1], Homeland Security, Mineral Exploration, to Environmental Control and Monitoring. Primarily, the technological advancements and monetary investments have been made by military forces across the world; this is due to the increase in demand for intelligence, surveillance and reconnaissance operations (ISTAR) in Iraq and Afghanistan [2]. As UAVs have the capability for short or long range surveillance and can be equipped with state-of-the-art electronic sensors, these systems have the ability to gradually diminish the use of live combatants in ISTAR operations.

As the use of small UAVs increase in the military, emergency, and recreational markets, so does the need to develop more technologically advanced systems. The flight time for the majority of rotary-winged vehicles is the Achilles heel of the system. It is evident that the efficiency of the propulsion unit is a key area of optimization with up to 90% of the total power produced by the UAV consumed by this system alone [3]. At the scale of small UAVs the use and optimisation of co-axial rotor systems is an area which is still undefined.

The co-axial rotor design offers many advantageous attributes over singular rotor systems. These areas are accentuated and highlighted when the design and optimisation of co-axial rotor systems at the SUAV scale is investigated. There is very little empirical data and evidence apart from a report by Coleman [4], and research

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conducted by a select few research and development labs at Universities across the world that identify the optimum conditions of co-axial rotor systems, especially at the SUAV scale. Even with the current research and data available it is difficult to predict the performance and therefore optimize a co-axial rotor system for a specified scale due to conflicting reports, which has stimulated the analysis of dimensional similarity. Recent co-axial rotor studies and doctoral theses rely heavily on outdated co-axial rotor system studies [5], theoretical modelling, and computational fluid dynamics [6]. Further to the lack of empirical data on co-axial rotor systems used on SUAV, there is also insufficient analysis of commercial-off-the-shelf components, i.e. outrunner motors and propeller matching, used on rotary-winged UAVs.

The aims of this paper are to develop an understanding of the optimum performance attributes of the co-axial rotor system at the SUAV scale; investigate the advantages and disadvantages of using co-axial rotor systems as a propulsion unit on SUAV, and to design and develop a co-axial rotor test-rig which will validate theoretical concepts and provide experimental data for rotary-winged SUAV.

1.1 Advantages and disadvantages of co-axial rotor systems

To understand the optimisation aspects of the paper and further develop the benefits of the co-axial rotor system used for propulsion on an unmanned aerial vehicle (UAV) a basic understanding of the advantages and disadvantages of the rotor system will be discussed.

As motioned towards by Coleman [4] and Syal [7] the single main advantage of the co-axial rotor system is the lack of a tail rotor. The tail rotor of a singular rotor system consumes up to an estimated 5-10% and at times 20% of the total power supplied by the engines. It is used by the system to counteract the yaw effect of the main rotor, for a co-axial rotor system the yaw cancelation derives from the contra-rotating rotors.

Further validation and investigations into the advantages and disadvantages are given below with examples discussed that are deemed most applicable to the SUAV co-axial unit development [8].

1.1.1 Co-axial advantages

- No drive train losses due to tail rotor absence.
- No possibility of tail rotor strike; a major cause of helicopter crashes.
- Shorter fuselage, small helicopter. The advantages of a smaller propulsion system to SUAV are obviously an area of great interest.
- Directional stability through cancellation of main rotor gear torque moment (Yaw torque reaction).
- Compact size through use of concentric shafts.
- Increased pressure differential over rotor system; increased thrust, higher efficiency for increase in thrust, which translates into a reduction in rotor diameter for a given thrust.

1.1.2 Co-axial disadvantages

- Complexity of linkages required to operate pitching control. This disadvantage is predominantly linked to full-scale aircraft, due to the developments discussed further in the paper; this is not wholly applicable to SUAV co-axial rotor systems.
- Inter-rotor wash interference. Reduced efficiency of the lower rotor due to the upper rotor swirling the air in the opposite direction of the lower rotor which requires the lower rotor to run at higher speed to produce the same lift as the upper rotor.

- Importance of flow interaction, requirement for rotor spacing. To ensure sufficiently clean flow for the lower disc, the spacing must be wide enough to allow as little interaction of the swirl of the upper rotor to impinge on the retreating component of the lower disc.

2. Co-Axial Propulsion Systems

From the recent developments of miniaturized propulsion technology, advancements in UAV control systems, and most prominently as the benefits of using a co-axial rotor configuration are being explored; co-axial systems are fast becoming the competitive choice of propulsion in the commercial and military UAV sectors. Developers of commercial and military Micro Air Vehicles (MAV) have taken the co-axial rotor system concept and produced simplified control systems to exploit the advantages of the co-axial rotor system, namely the systems stability, compactness and flight control characteristics.

Due to the co-axial rotor systems in-flight advantages over single rotor platforms, the technology is being explored and used by many companies and universities for research and developmental work at the MAV and SUAV scale. Examples include Pioneer a system developed by the Pixhawk team in the Autonomous Systems Lab at ETHZ (Swiss Federal Institute of Technology), which won the 2009 European Micro Air Vehicles competition (EMAV) in Indoor Autonomy [9]. The Pioneer MAV has been development in parallel with the muFLY project (see Fig. 1), which consists of a consortium of six partner institutions (including ETHZ) with the goal to develop a fully autonomous micro helicopter, comparable in size and mass to a small bird.

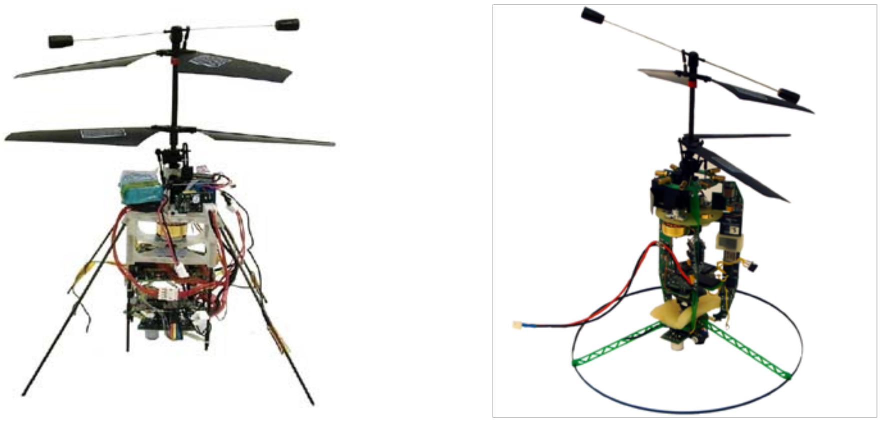

Fig. 1. V1.1 & V2.0 of muFly MAV [10].

ETHZ have also been in collaboration with Skybotix (a spinoff company from ASL at the Swiss Federal Institute of Technology, Zurich) and have helped develop CoaX™ which uses a very similar co-axial configuration to the Pioneer MAV [11]. Both systems use the co-axial rotor system from a Walkera HM 5#10 which has an H/D ratio of 0.189. Other research platforms from the Swiss Federal Institute of Technology include EPFL's co-axial helicopter designs from Masters Student Yves Stauffer [12].

The focus of this paper is the optimization of small UAV (SUAV) co-axial rotor system propulsion units. In effect these systems share a great deal of aerodynamic properties with the propulsion units developed by Skybotix and EPFL at the MAV scale. The major determinant of differentiation between the two systems is the SUAV simplifications of the UAVs coordinate control system i.e. the SUAV co-axial propulsion system replaces the mechanical control linkages for fixed-pitch propellers which are controlled by the flight control system of the aircraft to determine Yaw, Pitch, and Roll.

Fig. 2. Walkera5#10 rotor head [10], DraganFly X6 [13].

The fixed-pitch co-axial rotor system is in use with a variety of SUAV propulsion systems, with a diverse range of applications. Currently there are only a few developers which use the fixed-pitch co-axial rotor systems in their commercial SUAV. Dragonfly Innovations Inc., which is a Canadian UAV developer, manufactures co-axial SUAV that are developed for surveillance and reconnaissance missions in the commercial and law enforcement sectors. The co-axial systems they produce both use multiple co-axial propulsion units, with the X6 [14] using a tri-rotor configuration and the X8 using a quad-rotor [15] respectively. Both systems have an H/D ratio of approximately 0.25-0.26.

The use of the tri-rotor and quad-rotor configurations for co-axial UAVs are not solely used by Draganfly Innovations Inc., similar configurations such as Middlesex Universities HALO® UAV [16], H/D=0.47, also use a tri-rotor configuration. HALO® is predominantly fabricated from off-the-shelf components and is still in development within the Autonomous Systems Laboratory at Middlesex University. The development of the HALO® system includes research into multiple rotary-winged UAVs, namely variants of MikroKopters HexaKopter. The HexaKopter UAV is a widely used open source system where RC hobbyists have cannibalized and developed their own UAVs that use the multiple co-axial propulsion unit concepts.

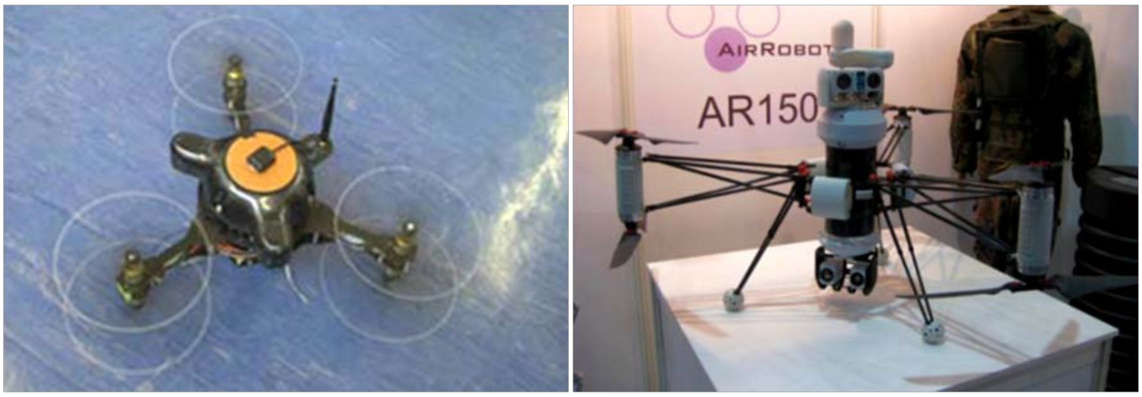

Fig. 3. ASL (Middlesex University) HALO® SUAV [16], Air Robot AR150 [17].

3. Co-Axial Rotor System Aerodynamics and Testing Variables

As aerodynamics and aeromechanics have the greatest influence on SUAV in-flight performance, this section is a summation of the core components that influence the co-axial rotor system in the flight condition of hover. Although the evaluation of forward flight is of interest, it is deemed too complex in regards to fabricating a controlled environment such a wind tunnel to be able to simulate these conditions and unfeasible within the constrictions of the project time limit.

The Figure of Merit (FM) when applied to a co-axial rotor system is a non-dimensional efficiency metric that provides a basis to conduct a relative comparison of rotor performance. The FM uses the "ideal" power required to hover (calculated using the moment theory) which is in turn equated against the "actual" power required to hover. Figure of Merit by Leishman [18] is given as follows:

$$FM = \frac{\textit{Ideal power required to hover}}{\textit{Actual power required to hover}} \tag{1}$$

Where:

$$FM = \frac{1.2657\dfrac{C_{T_l}^{3/2}}{\sqrt{2}}\left[\left(\dfrac{C_{T_u}}{C_{T_l}}\right)^{3/2}+1\right]}{K_{\mathrm{int}}K\dfrac{C_{T_l}^{3/2}}{\sqrt{2}}\left[\left(\dfrac{C_{T_u}}{C_{T_l}}\right)^{3/2}+1\right]+\dfrac{\sigma C_{d_o}}{4}} \tag{2}$$

In terms of the measured co-axial systems power, the definition for FM is:

$$FM = \frac{1.2657\dfrac{C_{T_l}^{3/2}}{\sqrt{2}}\left[\left(\dfrac{C_{T_u}}{C_{T_l}}\right)^{3/2}+1\right]}{C_{P_{meas}}} \tag{3}$$

Where:

$C_{T_u} + C_{T_l}$	=	Rotor Thrust coefficient (Upper, Lower)
$C_{P_{meas}}$	=	Rotor Power coefficient (measured)
σ^{+}	=	Rotor solidity
C_{d_o}	=	Minimum or zero-lift drag coefficient

Rotor flow fields discussed by Leishman and Ananthan [19] are referred to as the *vena contractors* of the upper and lower rotors; it is also referred to as the slipstream of the co-axial rotors. To minimise the interference-induced power factor using the momentum theory the co-axial rotor system is theoretically set in a condition of "the rotors operating at balanced torque, with the lower rotor operating within the *vena contracta* of the upper rotor" [20]. Leishman goes on to discuss the ideal flow considerations noting that "one-half of the disk area of the lower rotor must operate in the slipstream velocity induced by the upper rotor" [19]. The flow model of a co-axial rotor system and the vena contracta are detailed in Fig. 4.

The separation distance could therefore have an effect upon the severity of the interference-induced power loses, which would in turn possibly increase the efficiency rating (Figure of Merit) of the co-axial rotor system.

Taylor [21] discusses the contraction of the rotors wake, giving the ideal wake contraction ratio is 0.707. He also mentions that a rotor wake contracts within 0.25 of the radius of the rotors blade. Vortex wakes are also described in detail by McCroskey [22] where he presents an overview of the vortical flows around rotary-wing aircraft.

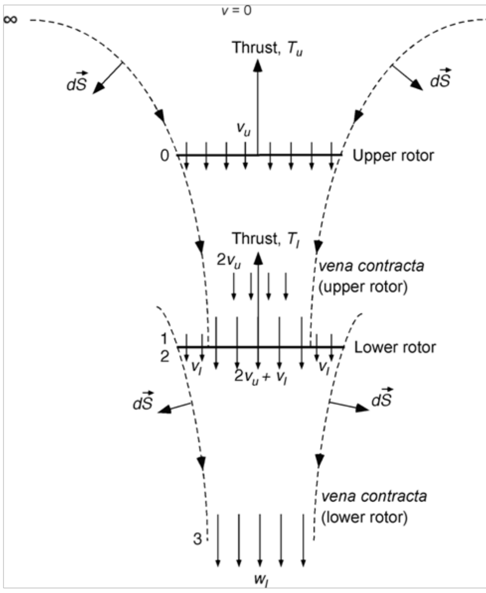

Fig. 4. Flow Model of a Co-Axial Rotor System [18].

The investigation of the co-axial rotor system will primarily revolve around four testing variables:

- **Inter-rotor spacing** – The separation distance (H) between the co-axial rotor system discs. Inter-rotor spacing is one of the fundamental components of the SUAV co-axial system which has been tested due to the associated aerodynamic effects; interference-induced power losses, wake contractions, and rotors *vena contracta*. The H/D ratio is used as a non-dimensional figure to enable comparison of multiple systems across a range of scales:

$$H / D\ ratio = \frac{Separation\ Distance\ (m)}{Rotor\ Diameter\ (m)} \tag{4}$$

Fig. 5 compares H/D ratios, incorporating full-scale co-axial helicopters down to MAVs. The table demonstrates that the SUAV example systems have a significantly higher H/D ratio (average H/D=0.315), when compared with the average full-scale helicopter systems having an H/D=0.09.

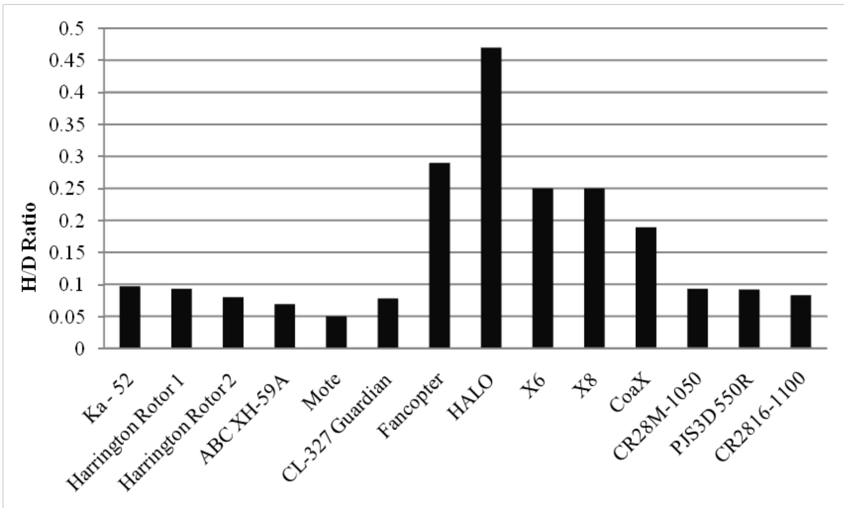

Fig. 5. H/D ratio comparison chart [23].

- **Propeller Pitch** - The propellers used in the co-axial tests are fixed pitch, but unlike full-scale rotor blades which have an almost uniform pitch throughout the diameter due the design preference of a symmetrical blade section [24]; the test propellers have a varying pitch.

  There has been little research into the twist distribution and pitch of commercially available propellers used in a co-axial arrangement, the majority of investigations focus on traditional helicopter planforms and blade design. Syal states that "*a higher blade twist is desired on the upper rotor to reduce induced losses of the co-axial unit, whereas a high blade twist on the lower rotor increases the induced losses*" [7]. On the contrary, commercially available co-axial rotor systems such as the Himax CR2816-1100 unit recommend an increase in the lower rotor pitch. The airfoil characteristics of a small scale co-axial rotorcraft were also analyzed by Samuel et al, where it was shown that profile drag accounts for 45% of the losses compared to 30% in full-scale helicopters [25].

- **Propeller Diameter** (upper and lower) - The diameter of a propeller is one of the most important characteristics in determining the induced power of a rotor system:

$$P_i = \frac{T^{2/3}}{\sqrt{2\rho A}} \tag{5}$$

  It has been shown in studies by Leishman that the larger the rotor diameter the lower the disc loading, induced velocities, and a decrease in induced power requirements [20]. Andrews [26] noted that an 8% reduction in upper rotor radius enhances the performance of the lower rotor due to an increase of exposed clean air. This variable will be controlled only using a select "family" of propellers to determine the performance attributes related to the decrease of the upper and lower rotors.

- **Co-Axial System Torque** - One of the prominent attributes of a co-axial helicopter design is its ability to control yaw without the use of exterior actuators, i.e. a tail rotor. A detailed description of a traditional helicopters control and flight coordinate system, pitch, roll, altitude, and yaw are given by the Rotorcraft Flying handbook [27].

  A senior engineer at Kamov described the comparison of the co-axial helicopter to the traditional singular rotor system:

  "*As far as power is concerned, the coaxial helicopter has a considerable edge over its single-rotor counterpart, since all free power is transferred to the rotor drive, i.e. used for developing the lift, while the single-rotor helicopter's tail rotor power consumption accounts for 10-12% of total power*" [28].

3.1 Propeller characterisation

The propellers used in the co-axial rotor system testing will primarily consist of commercially available components from a range of manufacturers. Propeller design is a very complex subject area, especially considering the co-axial rotor system which has two propellers thus introducing an increased range of variables and aerodynamic properties to consider.

To enable the characterisation of a propeller the determinants of performance need to be defined. The tool used for these measurements will be the Hyperion Emeter. The Hyperion Emeter determines the performance of a propeller by using two groups of propeller (prop) constants, thrust constants and factors, and power constants and factors. These constants are used to estimate a specified propeller and motor combinations efficiency and performance, calculating thrust and output power at a given input power.

3.1.1 Power constants and factors

An optimally matched motor and propeller combination would be a system that creates as much thrust as possible from the smallest amount of power. To establish an efficiency figure from the motor and propeller combination the Hyperion Emeter uses the traditional efficiency equation of:

$$Efficiency(\%) = \frac{P_{out}}{P_{in}} \times 100 \tag{6}$$

Where:

P_{out} = Power Output (W)
P_{in} = Power Input (W)

The power output of the system is calculated using the Emeter via entry of the power constants and power factors of the propeller. These components are calculated using data derived from tests measuring the reaction torque of the motor when driving a propeller at a given speed.

The power constant and factor of a given propeller and motor combination is determined from a power trend curve equation in Excel. The power constant is often referred to as having a cubed law relationship the rotational speed of the propeller (RPM).

Fig. 6 depicts the process of testing the reaction torque of the AXI 2217/20 motor and GWS 1060X3 HD propeller combination. The Output Power is calculated by the Emeter by using the following equation, which can be determined by using one empirically derived figure (RPM):

$$Output\ Power\ (W) = Power\ Constant \times (RPM \times 1000)^{Power\ factor} \tag{7}$$

To calculate the constants the following formula and method of extrapolation is applied:

The torque test-rig design enables the motor and propeller to be suspended in between two upright plates that hold the mechanism axially in-between two radial bearings. The measurement of reaction torque is derived from a simple lever mechanism attached to the (usually) stationary end of the out-runner motor which in turn presses down on a set of digital scales. This lever arm is measured at 4.87 cm (radial distance) which is used to derive the required torque to drive a specified prop at any given RPM:

$$Output\ Power = \frac{measured\ scale\ thrust \times RPM}{constant\ \ factor} \tag{8}$$

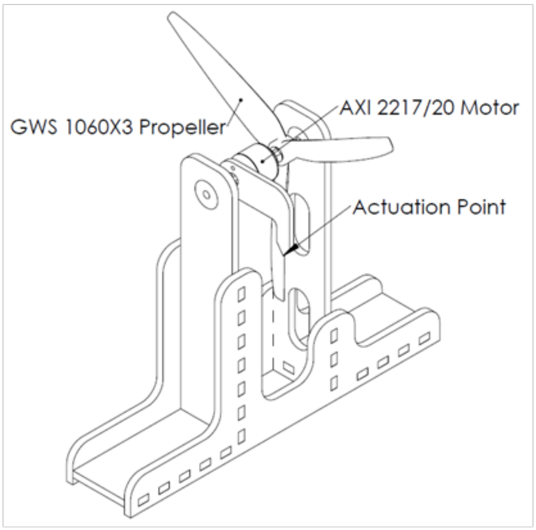

Fig. 6. Motor torque test-rig.

The constant factor is a derivative of the Torque equation:

$$Power\ (W) = RPM \times \frac{gram.cm}{97400} \tag{9}$$

The lever length, depicted in Fig. 6 as "actuation point", is measured at 4.87 cm, and is used to derive the constant factor:

$$Constant\ Factor = \frac{97400}{0.0487} = 19988.197 \tag{10}$$

Once the process of establishing the power output is completed, the data can then be plotted against the rotational speed of the propeller to extrapolate the Power Constant and Power Factor via a power trend line in Excel.

3.1.2 Thrust constants and factors

The thrust constant and factor are derived from a similar process to that of the power constant and factor apart from substitution of output power for measured thrust (measured in grams) to plot a thrust performance graph. The power trend line function derives both the factor and constant of thrust. It should be noted that the thrust test which measures the lifting force at a given current of the motor and propeller combination is to be tested in static conditions. To give a true valuation of the configurations performance the test should be simulated in a wind tunnel environment.

4. Test-Rig Development

To be able to validate the testing variables and develop an understanding of co-axial rotor systems on small SUAV the test-rig and testing components will need to be able to fulfil all the testing variables and co-axial rotor configurations.

Co-axial rotor systems in the western hemisphere are still undefined and limited (in comparison to the studies and development of single rotor systems) in their explanation of their aerodynamic and aeromechanical principles. As discussed earlier in this paper the existing studies on co-axial rotor systems primarily focus on full-scale systems, and only recently has there been renewed interest in the development and possible application of the benefits surrounding co-axial rotor systems at the small UAV scale.

Recent developments in the co-axial rotor system for the small-scale UAV sector could have resulted from the technological developments in RC propulsion units [8]. One of the earliest recorded co-axial UAV studies was work commenced by Andrews [26] on a Westland Helicopter Ltd developed system called Mote, the systems handling and control qualities are discussed in detail by [29]. It was these studies by Andrews [30] that demonstrated a decrease of 8% to the upper rotor radius enables "the enhanced performance of the lower rotor as proportionately more disc is exposed to clean air". Andrews also discussed the inter-rotor spacing stating that there are no practical gains after H/D=0.05.

More recent test-rigs and co-axial rotor system investigations include the work of the Autonomous Systems Lab (ASL), ETH at Zurich. The extensive work produced by this team has been spearheaded by Bouabdallah. The significant research systems/platforms developed by the ASL at ETH are CoaX and CoaX 2, both co-axial MAVs. Unlike many co-axial rotor studies the muFly team has designed and built their own co-axial rotor test bed, and recorded the study in detail. A similar system which enables the investigation of MAV co-axial rotor systems is the rig developed by the University of Maryland for the MICOR MAV. Both systems are designed for variable pitch rotor heads.

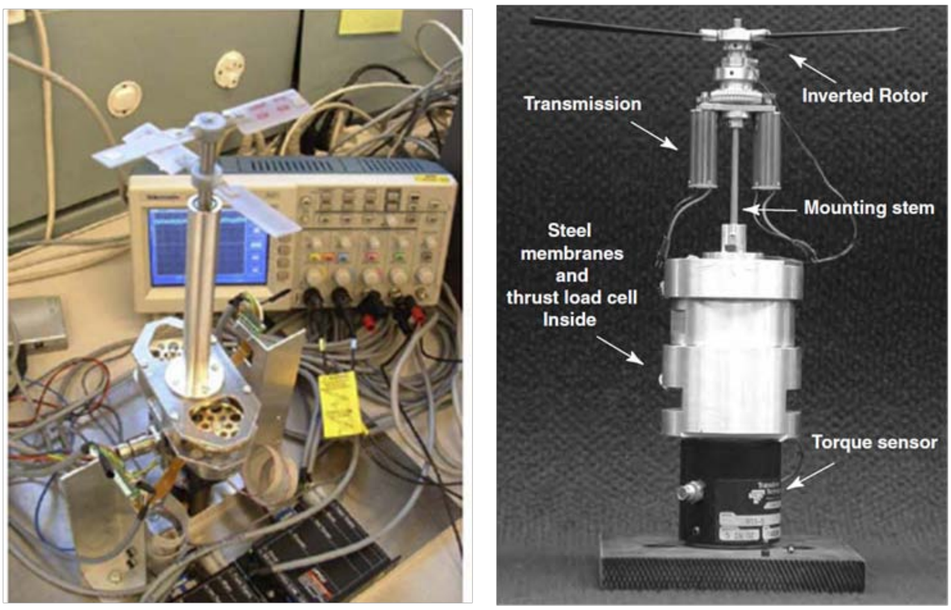

Fig. 7. muFLY [3] & UMD MICOR co-axial rotor system test-rigs [31].

The test-rigs priority is to be able to test and measure various co-axial fixed-pitch rotor system configuration variables. The components used in the setup for a co-axial rotor system (using HALO's components as a datum) have dictated the majority of the test-rigs overall design. The motors used for the co-axial rotor system are the AXI 2217/20 electric Outrunner DC motors, which are inherently stable and give good efficiency ratings (~ 82%) [32]. The propellers used range from dual-bladed, low pitch and slow fly APC 10″ propellers up to 12″ Master Airscrew tri-bladed propellers. The range encompasses five "families" of propellers, each with their own performance benefits, and bought in especially for a specific testing process.

Taking into account the co-axial rotor systems testing variables, and the known datum components set by the HALO configuration, mechanical solutions were developed. Linear motion technology in the form of a motor driven lead-screw system was chosen to vary the inter-rotor spacing of the co-axial rotor configuration. The desired range of inter rotor spacing stemmed from using the GWS 1060X3 (10 inch diameter propeller) as a datum (i.e. 254 mm). With this size of propeller was used, the H/D ratio could be varied between (0.08–1.0).

To establish the optimum lead-screw diameter for the co-axial test-rig a logical range of lead screws diameters were initially considered. One of the predominant requirements of the system was the overall mass of the test-rig, and as the lead-screw is one of the only components fabricated out of medium carbon steel the selection of the correct component was crucial. The 12 mm diameter lead-screw was selected due to its high efficiency rating, low mass (kg) per metre, and its relatively low linear distance travelled per revolution (3 mm).

For the measurement of thrust (g) the Autonomous System Lab's thrust testing rig was incorporated, which works on a fulcrum lever principal. One of the foundation attributes for the co-axial rotor systems experiments is to be able to test if the configuration is in the condition of equal torque, the test-rig will incorporate a yaw effect measurement system. The design feature enables the user to visually recognize if the system is in the condition of equal torque by using simple rule measurements. As the co-axial test-rig is attached to the ASL thrust testing rig, the bracket to which will attach the two systems also doubles up as the pivoting point for the Yaw gauge.

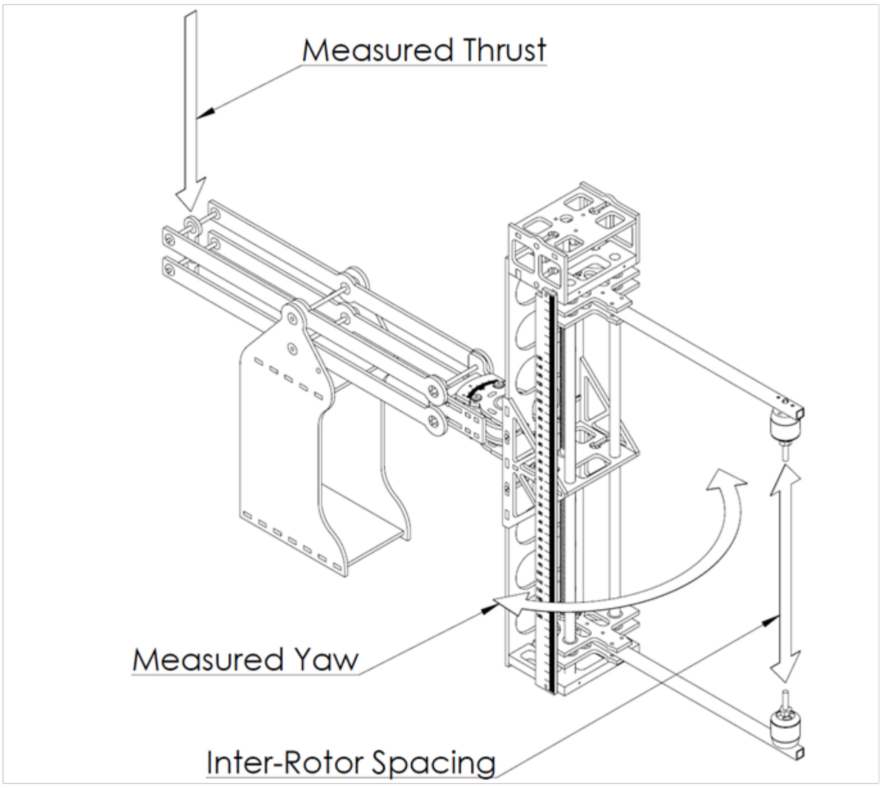

Fig. 8. CAD Model of the Co-Axial Test-Rig [23].

Fig. 9. Yaw mechanism attached to thrust bracket.

The optimization process of the co-axial rotor system has continually taken place as the testing commenced. To develop a portfolio of test data from the testing components, analyze the efficiency of particular component configurations and testing conditions a data logging and live monitoring tool has been employed. The Hyperion Emeter II is a high performance measurement tool which is able to measure, analyze, and log key performance factors used in electric systems and RC models. The Emeter is supplied with a remote data unit (RDU) which houses a high precision shunt that is capable of accurately handling high currents and voltages, and is able to feed theses data attributes back to the Emeter for evaluation purposes. As an overview a block diagram of the co-axial test bed is depicted in Fig. 10.

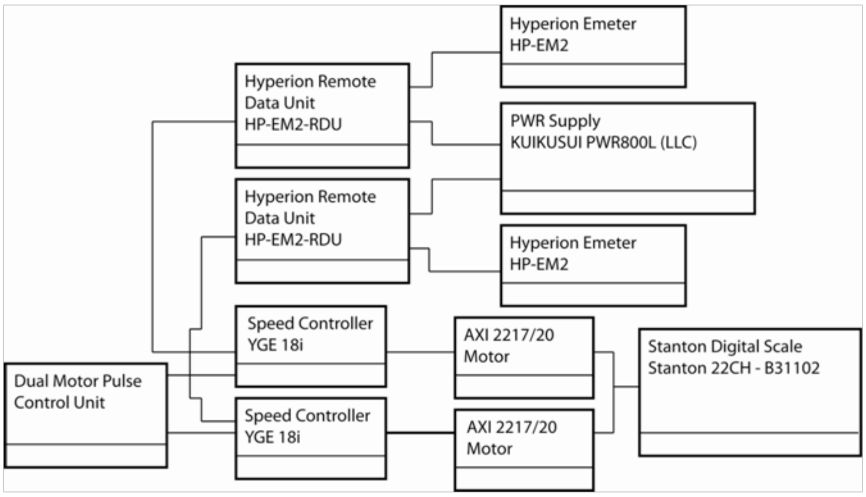

Fig. 10. Block diagram of co-axial the test-rig.

5. Performance of a Co-Axial Rotor System

To be able to test the co-axial configuration in the optimal motor and propeller arrangement a series of tests containing various co-axial configurations were analyzed. A comparison data set consisting of individual rotors at multiple orientations used in the co-axial configurations gave a datum result for each singular rotors performance. Eight configurations were tested for the optimal motor and propeller configuration for a co-axial propeller system, with only four having contra-rotating rotors.

The highest performing co-axial configuration, when plotting the measured system Thrust (g) Vs Speed (RPM×1000), was when the motors are placed on the outside of each mounting arm on the test-rig using an upper – Pusher propeller, and lower – Tractor propeller setup. A similar overall performance measurement was seen when plotting Output Power (W) Vs Speed (RPM×1000). This data coincides with the finding of Shkarayev [33], where the rotor configuration used on the SUPAERO MAV showed a 20-23% thrust increase when using a pusher configuration when compared to a tractor configuration.

As co-axial rotor systems are compared to their singular counterparts in numerous studies, a study of the individual rotor and motor configurations used in the co-axial testing has also been undertaken. The points of interest and observations are detailed below:

- When comparing the co-axial rotor configurations measured Thrust against the combined two singular rotor systems measured Thrust, the average Thrust output is 23.15% lower.

- The Thrust/Current Ratio of the co-axial rotor system averages a 2.22% decrease per amp when compared to the combined singular Rotors.

- Although configuration No. 6 (see Fig. 11) showed the most promising results the setup of the configuration would not be able to reach the small inter-rotor spacing's required. Considering this issue, the configured system for the co-axial H/D testing was setup to the same propeller placement (Upper–Pusher, and Lower–Tractor) but placing the motors facing inwards.

- Independently the individual tests of each singular rotor comparison gave unexpected and interesting results. Prior to the experimentation phase it was thought that a tractor and pusher propeller operate in an identical fashion i.e. producing similar Thrust, and Output Power performances (allowing for the inaccuracies of the rig, and data logging). Fig. 12 depicts the performance variation of the Tractor and Pusher GWS 1060X3 HD propeller in two configurations for each type of propeller. The pusher propeller placed on the upper arm had a thrust increase (at 7,000 RPM) of 7.11% compared to the Tractor Propeller; this trend was also observed on the lower rotor comparison, with the Pusher variant producing 8.29% (at 7,000 RPM) more thrust than its tractor counterpart.

Using the optimally determined configuration for the co-axial rotor system, inter rotor spacing tests were commenced with a range from 20 mm to 250 mm (0.08< H/D <1.0) at 10 mm increments. The system was operated at an unequal torque and thrust balance, with the objective of the testing to establish a co-axial rotor systems static thrust capabilities at a given H/D ratio. As the research is to coincide with the development of ASL's HALO® the propeller and motor combination of primary interest were the GWS 1060X3 HD and the AXI 2217/20.

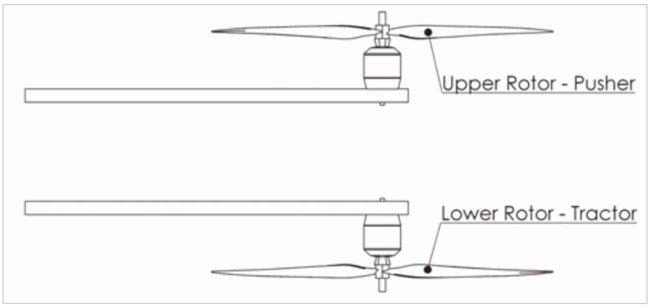

Fig. 11. Configuration No.6 (PUU & TLD).

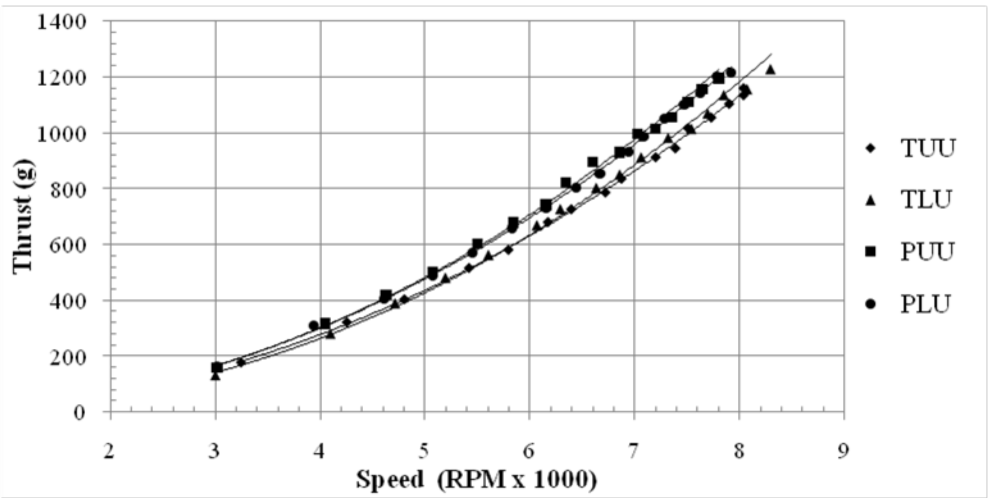

Fig. 12. Individual motor configurations - Comparison of tractor and pusher propellers.

Fig. 13 shows a select region of H/D ratios which provide a measurable increase in Thrust at a given Current (A). A range of 12–14 A was used to plot the variation in Thrust Vs H/D ratio, with H/D ratios of 0.45 and 0.57 showing the least fluctuation and range.

The main observations to be drawn from the H/D testing are summarised below:

- The inter-rotor spacing does have a limited effect upon the total thrust of the co-axial rotor system, with a maximum variation of 4.67% (at 14 A, using 0.08< H/D <0.41).

- A similar trend in the performance of Power Output (W) was seen when plotted against speed (RPM×1,000), with a range of H/D ratios of (0.41-0.65).

To validate the findings of Andrews [26] where his studies have shown a reduction of 8% in upper rotor diameter increases the overall performance of the co-axial rotor system due to the lower rotor disc being exposed to clean air. A series of diameter reduction tests were initiated using the GWS propeller range.

To be able to characterize the performance of each co-axial rotor systems reduction of the upper rotor the measured Thrust (g) of each unit was compared to their singular equivalents combined theoretical Thrust (g). The overall comparative Thrust loss was calculated and plotted in Figure 14, where a 10% reduction in upper rotor diameter displayed the lowest overall thrust losses. The results also highlighted other system characterizations:

- An 11.15% reduction in upper rotor diameter showed limited but measurable performance benefits when compared to the 1060/1060 co-axial configuration (IRS 120 mm), with an average 1.2% increase in thrust.

- An increase in upper rotor diameter displayed poor performance qualities, with the 20% increase in upper rotor diameter demonstrating a 29% overall thrust loss.

Rotor pitch analysis of the co-axial rotor system used the APC Sport propeller range. The test consisted of a series of tests alternating the pitch of both the upper and lower rotors, keeping the APC 10×6S propeller throughout. The observations derived from these tests are discussed below:

- Fig. 14 plots the trends of the rotor speed difference (upper rotor / lower rotor) versus the measured system thrust. It is clear that increasing the lower rotors pitch, in this case by 33.3%, decreases the lower rotors RPM by 17%, with the opposite configuration having a lower rotor RPM increase of 10%.

- Recent research has stated that: "For propellers with propeller Pitch/Diameter ratios greater than 0.6, the static thrust is relatively constant regardless of pitch" [34] i.e. a 10×6, 10×7, 10×8, 10×9 and 10×10 all have approximately the same static thrust at the same RPM. This observation by McKinney holds true for the upper rotors tested in the pitch analysis.

- Syal [7] varied the testing with regards to increasing the upper rotor blade twist to reduce induced losses of the co-axial unit. With the highest performing configuration in output power with an increase in the upper rotors pitch by 33.3%.

An area which hasn't been tested but is of interest is the co-axial rotor systems ability to equalize the reaction torque of the system using a pitch variation between the rotors. This has been quantifiably measured by Schafroth at ETH Zurich, where his findings show that "less rotational speed is needed in order to have equal torque for higher pitch angles" [10] he also goes on to describe a trade-off between a lower power consumption Vs. a reduction in thrust, with the results of the 18° pitch angle giving the highest thrust to power ratio (see Table 1).

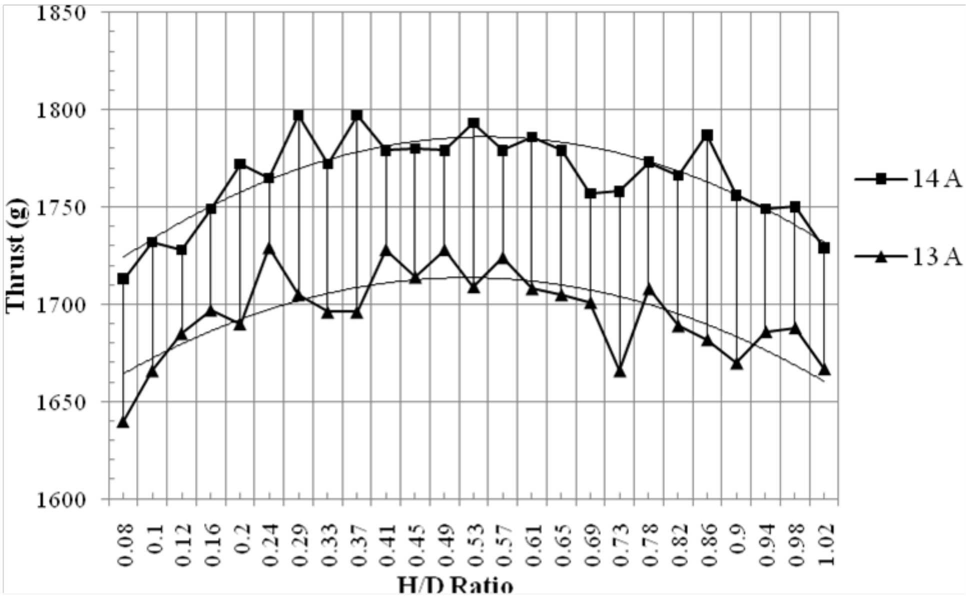

Fig. 13. Variation of co-axial thrust with rotor spacing.

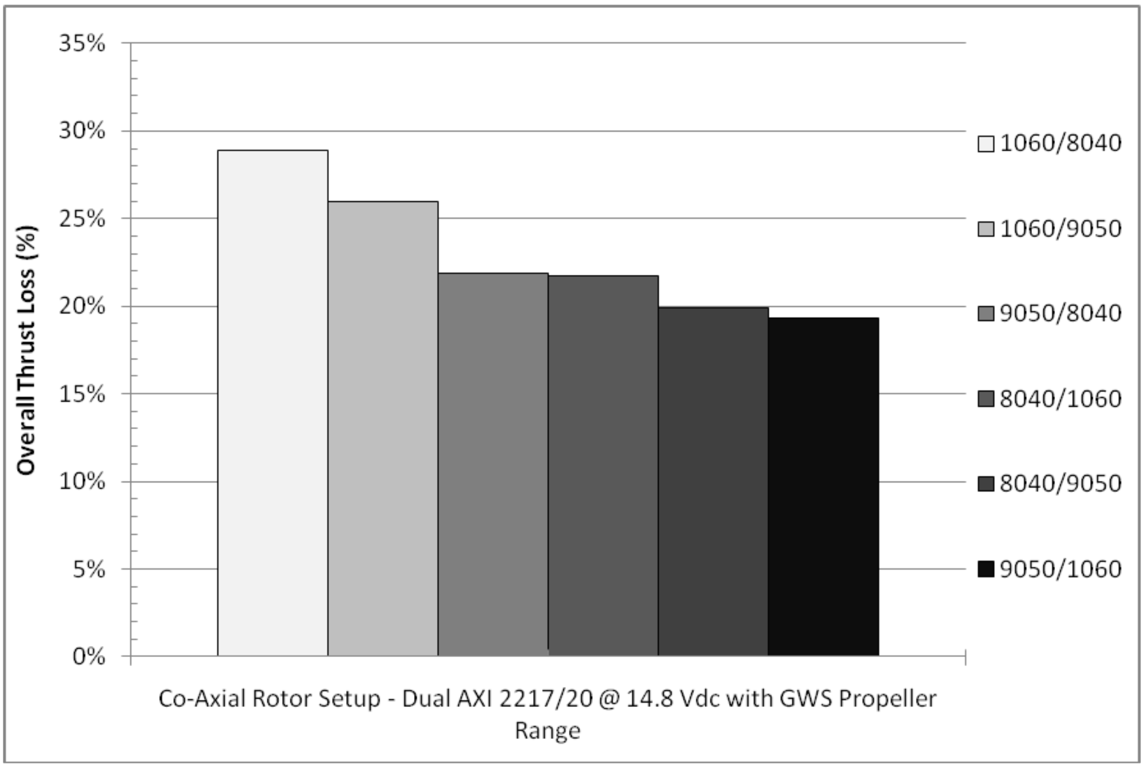

Fig. 14. Variation of co-axial thrust with rotor spacing.

Table 1. Influence of different pitch angles on the lower rotor [10].

Angle (deg)	Speed (RPM)	Thrust (N)	Power (W)	Thrust/Power (N/W)
14	6,650	0.1949	2.0531	0.0950
16	5,750	0.1820	1.7413	0.1042
18	5,025	0.1709	1.5286	0.1118

The condition of zero yaw of the co-axial rotor system was acquired by setting the upper rotor RPM at a set value and then matching a lower rotor RPM until the system was at an equal torque condition. Due to the lack of a system mounted reaction torque sensor the tested co-axial systems initially required a formula to calculate the reaction torque of the individual motor whilst in operation. This formula was also used in the Power Constants to theoretically calculate torque.

The following table shows the formulas accuracy, using a sample from the GWS 1060RX3 Propeller and AXI 2217/20 motor results.

Table 2. Torque measurement data (GWS 1060RX3 Propeller and AXI 2217/20 Motor).

Measured Torque (Nm)	Theoretical Torque (Nm)	Torque Error %
0.107	0.100	6.28%
0.116	0.108	6.79%
0.127	0.119	5.93%
0.132	0.128	3.27%
0.146	0.139	4.68%
0.151	0.149	1.44%
Average Error (assessing entire range)		2.47%

In Configuration 1 (H/D=0.47) the rotational speed of the upper rotor was fixed at RPM=5,005 which was then matched with the lower rotor rotational speed of RPM=6,960 to enable a system in equal torque condition. Notably the calculated mechanical power consumption the lower rotor induced 59.7% more power compared to the upper rotor.

Four H/D ratios were tested to see if the variation of inter rotor spacing had a measurable effect upon the Output Power of the co-axial rotor system. Fig. 15 portrays the variation in output Power of the varying H/D ratios vs. the systems torque variation between upper and lower rotor. A trend can been seen throughout the systems with the percentile torque variation of the rotors initially increasing in a linear fashion but eventually levelling out towards the upper performance echelons.

4. Conclusion

There have been multiple areas explored in the process of optimizing a SUAV co-axial rotor system, some which have had limited research exposure and others which have been detailed thoroughly.

One of the main areas of interest and which has had the greatest influence on the co-axial tests-rigs design was the inter-rotor spacing attribute of the co-axial rotor system. The H/D ratio has been prominent in many significant papers, but lacking an empirical value or an optimal dimensionless condition. In this paper the H/D ratio of a SUAV has been explored thoroughly, reviewing the systems performance at incremental stages, the findings from this study have shown that a range of H/D ratios in the region of (0.41-0.65) is advantageous in the performance of SUAV systems. This finding lends itself to the theory of inter-rotor spacing is a non-dimensionally similar figure, which cannot be applied across a spectrum of systems; this could be attributed to the viscous losses of flight at low Reynolds Numbers (<50,000).

Notable areas that have been shown to have an important effect in the optimization of a SUAV co-axial rotor system are summarized below:

- A reduction in upper rotor diameter of 11.15% decreases the induced thrust losses of a comparative co-axial rotor system by 2%. This figure could be improved if the diameter increase had more incremental steps.

- The optimal positioning and propeller orientation has been shown to be via mounting the outrunner motors on the exterior of the systems with the upper propeller being a pusher, and the lower propeller being a tractor. This configuration displayed an overall thrust loss of 23.15% when compared to its singular counterparts.

- The rotational speed of the lower rotor when balanced at an equal torque condition is increased by 24%, which in turn has a calculated increase in mechanical power consumption of 59.7%.

- Increasing the lower rotor pitch decreases the lower rotor rotational speed, and when considering the statement above would in turn decrease the consumed mechanical power of the lower rotor.

- On the contrary to the statement above the system with the highest output power had an increase in rotor pitch of 33.3%, as discussed by Schafroth [10] there will inevitably be a trade off in thrust vs. system efficiency.

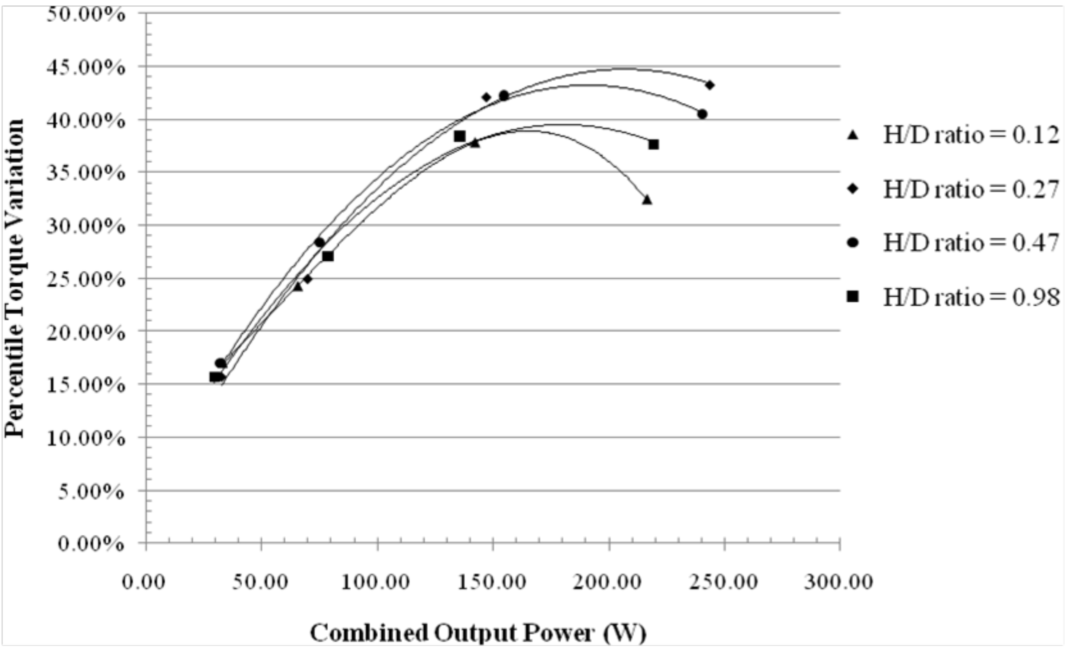

Fig. 15. Percentile torque variation versus combined output power.

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